High Precision Astrometry of Minor Planets and Natural Satellites

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Abstract

Humans have been noting the positions of celestial bodies in the sky since the very first time we looked up at night. Astrometry, the measurement of celestial positions, is used today for many purposes. This paper examines the techniques used to obtain astrometric measurements of solar system bodies such as asteroids and natural satellites, and how these measurements can be used in both the characterization of asteroids and in planning for future NASA missions to these solar system bodies.

I. Introduction

The position of stars in the night sky has always played an important role throughout human history. Ancient cultures kept track of the stars' positions by creating asterisms and constellations in order to understand the changing of the seasons. Hipparchus discovered the Earth's precession by taking very accurate measurements of stellar positions. Later on, Johannes Kepler used the positional measurements of Mars made by his predecessor, Tycho Brahe, to develop his laws of planetary motion. Astrometry is study of these celestial positions [1].

Today, NASA scientists use the positions of the stars to navigate spacecraft to bodies deep within our solar system. Missions like New Horizons, and the upcoming Psyche and Lucy missions, rely heavily on ephemeris data of solar system bodies to make sure the spacecrafts reach their targets. This paper details the steps that I and my partner, Stephanie Toole, under the mentorship of Dr. William M. Owen, Jr., took to update the ephemerides of asteroids and natural satellites within our solar system.

II. Location and Equipment

Our observations this summer were primarily made on site at Table Mountain Observatory, though some observations were done remotely at the Jet Propulsion Laboratory in Pasadena, Ca. Located near the town of Wrightwood, Ca, at an elevation of 7500 ft., TMO is an active research center where optical communication, atmospheric monitoring and astrometric studies are being done by scientists from Cal Tech, JPL and regional educational institutions. Our research was done using the Astro Mechanics 0.6m f/16 Ritchey-Chrétien reflecting telescope housed on-site in building TM-12. Imaging was done using a thermo-electrically cooled Finger Lakes Instrumentation Proline PL16803 CCD imaging array. This is a 16.8 megapixel (4096x4096) camera with a 9 µm pixel size. With this setup, we are able to obtain an approximate 13 arcmin FOV with a resolution of approximately 0''.2/pixel.

Our equipment was controlled using a host of different software utilities on a Windows PC platform. The telescope was calibrated, pointed and slewed using TMO's proprietary Telescope Control Program. The camera was operated using the Maxim DL software suite.

III. Observations

We were scheduled for three-night observation runs every other week at TMO throughout the summer. We would have had five different runs, but two of them were cancelled due to inclement weather and smoke traveling from fires in Southern California. In addition to the three runs at TMO, we also did a few random nights of imaging remotely from JPL.

The observation process started prior to our arrival at TMO. The first step was to make predictions of where our targets would be during the imaging process. Astrometric predictions were made using a program called Trajectory Geometry Program, which is classically used in the optical navigation of spacecraft. A script called UPDATE was run to set the dates of observation in order to predict the position of our targets during our observation runs. Three different updates were made for each night, each four hours apart from each other, so that we made sure to capture the target in our FOV at the time the images were taken. Once generated, the prediction plots were then viewed using a program called Ghostview, and printed out for use at TMO.

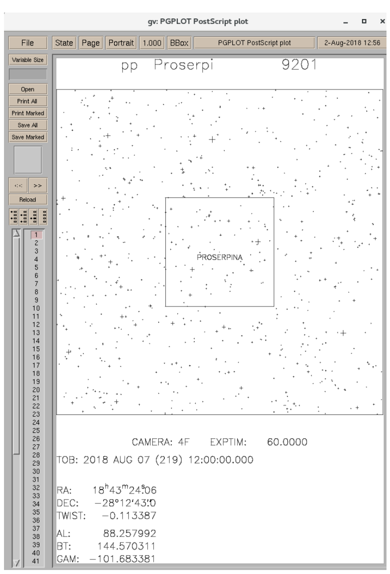

Figure 1: *Prediction plot of asteroid Proserpina viewed in Ghostview software*

Targets were chosen based on a few different criteria. First, we chose targets such as asteroids that would be occulting a star in the near future, in order to update the ephemeris of each asteroid in advance of the occultation event. (These occultation events are discussed more in the conclusion section below). We also chose targets that are potential objects for exploration in future NASA missions, such as the asteroid Psyche, certain Trojan asteroids and Saturn's moons. Finally, we chose targets based on their Declination coordinate being accessible from TMO, the number of background reference stars in the FOV, and their magnitude.

Each night of observations began shortly after sunset. From the control room in TM-12, we fired up the programs needed to control the dome, telescope and camera. The first step was to make sure our camera was properly focused for the night. To do this, we used an astrometric catalogue to locate a faint star near the zenith. We would then take a ten second exposure of that star. The Maxim DL software displayed a profile of the light coming from that star, and our goal was to make that light profile as sharp as possible. Once we were satisfied, we centered the star in the imaging window and calibrated the telescope to its position. We were now ready to star imaging our targets.

For each target, we would take a series of two or three three-minute exposures, depending on the number of reference stars in the background. Each image was offset by up to 15 arcseconds of Right Ascension and up to three arcmins of Declination to capture a slightly different set of reference stars in the background. For each image we took, we logged the RA and Dec of where the telescope was pointed, along with the target prefix, in a *"point"* file. We also recorded the temperature, barometric pressure and humidity during the span of time we spent imaging each target in a *"temp"* file. Weather data was obtained from a weather station at TMO.

Each night, we also took a series of calibration images. These images were used in the data reduction process so that the scripts could understand exactly how the telescope and camera were behaving on any given night. The calibration field should contain as dense a star field as possible. We used M11, the WIld Duck Cluster, as our calibration field throughout the summer, as it contains approximately 2900 stars!

Imaging would proceed until about half an hour before sunrise. As we wrapped up, we would stow the telescope, return the dome to its home position and close it, save all our data logs and record a brief description of our night in the observation log.

IV. Data Reduction

After we finished our observation runs, we would then return to JPL to start the data reduction process. This process was highly automated with a series of scripts, many built by Dr. Owen, doing most of the work for us. While there were many steps involved in this process, the work was broken down into three main parts: centroiding the images, identifying the stars and targets in the images, and reducing the xy coordinates of the targets into RA and Dec coordinates [3].

After transferring the image files, which were saved to the server at TMO, to our local server at JPL, the first script we ran was simply called DOIT. This script called upon four other scripts. First, the PREPARE script reformatted and renamed each image, incorporating the data from the *"point"* file. Next, the AMPTEMP script incorporated the data from the *"temp"* file, solved for atmospheric distortions, and created Input files for each target. The CENTROID script would find the center of every star-like figure in each image, including the target itself if found. Finally, the REDUCE script would call upon four other scripts to attempt to finish the automated process.

The first step in the REDUCE process was the TGP script. This script would provide predictions for the RA and Dec coordinates of the stars and target in each image. Once that was done, the AMP script would compare the CENTROID results to the TGP predictions and create a file with a list of the positions of every identified target, catalogued star and uncatalogued star in each image. Finally the REDUCE script called upon the AOGP and ADAP scripts. These were the two workhorses of the process. AOGP would calculate the expected image location and then calculate the partial derivatives of the image location based on the calculated parameters. The ADAP script then used a least-squares method to calculate the best fit for the target [3].

The scripts were not always able to locate the target in every image. This is where the power of the human mind would come in. After DOIT had finished doing its job, we ran a script called CHECK which would check to see that the number of targets found matched the number of predicted targets and the number of images of each target. If things did not match up, that meant that we would have to attempt to find the target in the image ourselves. A program called Xrover was used to do this. Xrover allowed us to bring up each image where a target was not identified, along with an overlay created from the TGP data which showed us the position of each catalogued star along with the predicted position of the target within the frame. We would manually move the overlay until it matched up with the underlying image. This would usually allow us to find the position of the target, unless it was too faint to show up in the image.

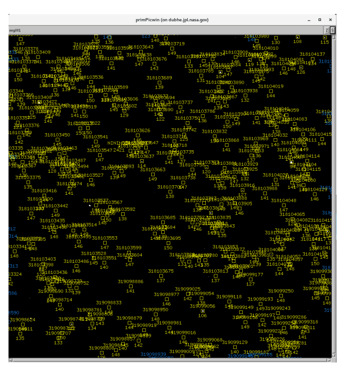

Figure 2: *Xrover view of TGP overlay used to manually pinpoint target*

Next, we ran a script called FINDBAD. This would identify all the bad residuals in each image which were affecting the accurate target position calculations. We would then go into the Input file for any image with bad residuals and comment out the stars producing those residuals. This would tell the scripts to ignore these stars. We could also comment out the target itself from each image if it was too faint to show up.

After this was done for each image with an unidentified target and/or bad residuals, we then ran the REDUCE script again until CHECK and FINDBAD came up clean. Once we were satisfied with the results, we prepared them for delivery to the Minor Planet Center using a script aptly named DELIVER. This would reduce all the data from every image into a single line of data for each identified target containing the updated RA and Dec coordinates for each target. Results were emailed to the MPC by Dr. Owen. Finally, we would run one final script called CLEANUP which would compress and archive the images and data.

V. Results

Over the summer, we took a total of 678 images of 145 unique objects. From those images, we were able to obtain 519 positions. All of this culminated in seven successful deliveries to the Minor Planet Center. Below is a sample of our published results.

(156) Xanthippe = 1901 SA = 1902 VA = 1936 FG1 = 1942 RP = 1949 BN

Discovered at Pola on 1875-11-22 by J. Palisa.

Orbit

Orbit type: Main Belt

Date (UT)	J2000 RA	J2000 Dec	Magn	Location	Ref
2018 07 24.365972	20 35 00.923	-03 38 20.58		673 – Table Mountain Observatory, Wrightwood	MPS 907954
2018 07 24.368287	20 35 00.791	-03 38 20.73		673 – Table Mountain Observatory, Wrightwood	MPS 907954
2018 07 26.392477	20 33 10.927	-03 41 16.87		673 – Table Mountain Observatory, Wrightwood	MPS 907954
2018 07 26.394896	20 33 10.791	-03 41 17.12		673 – Table Mountain Observatory, Wrightwood	MPS 907954

Figure 3: *Composite of our published results for asteroid (156) Xanthippe on MPC website on July 24 and July 26 [4]*

In addition to updating the ephemerides of minor planets, we also attempted to do the same for the natural satellites of Saturn and Mars. For Saturn, we were successful with six of its satellites: Titan, Rhea. Tethys, Dione, Hyperion and Iapetus. We attempted imaging Mars' satellites, Phobos and Deimos, on three different nights near opposition in late July but were unsuccessful on all three nights.

VI. Conclusion

The results produced from our research this summer can potentially be used for a couple different purposes. Future NASA missions to minor planets such as Psyche and the Trojan asteroids will rely heavily on accurate ephemeris data. Predicting occultation events is another important application of our results. An occultation occurs when the light from a distant object is temporarily blocked by another object passing in front of it from the point of view of the observer. In particular, we are concerned with the occultation of a star by one of our observed objects. Our results can help amateur astronomers around the world determine whether an events path will pass over their location. When enough observations of an event are made, they can be pieced together to help us characterize the shape and size of an asteroid. In the image below, the binary asteroid (90) Antiope is shown occulting the star LQ Aquarii, observed from more than 50 different unique locations [2]. Each colored line is a separate observation.

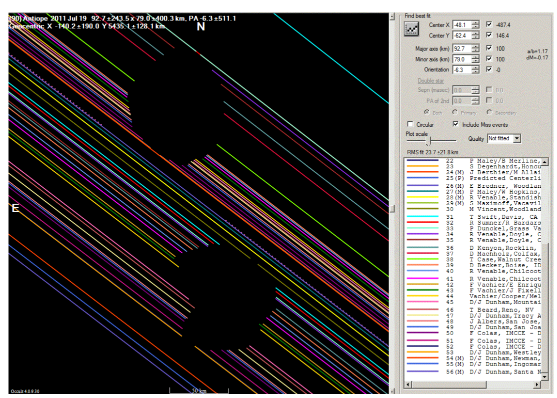

Figure 4: *Occultation of star LQ Aquarii by binary asteroid (90) Antiope [2]*

VII. Acknowledgements

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